Beyond the Crystal Maze: Twentieth-Century Physics from the Vantage Point of Solid State Physics

Joseph D. Martin[*] and Michel Janssen[†]

"Where, then, is that person who ignorantly sneers at the study of matter as a material and gross study? Where, again, is that man with gifts so God-like and mind so elevated that he can attack and solve its problem?"[1]

— Henry Rowland

Solid state physics did not exist when Henry Rowland, founding president of the American Physical Society, wrote the above lines in 1899.[2] Rowland instead referred to late-nineteenth-century struggles to understand the structure and behavior of atoms and molecules.

---

[*] Lyman Briggs College, Michigan State University, 35 East Holmes Hall, 919 E. Shaw Lane, East Lansing, MI 48825, jdmartin@gmail.com.

[†] Program in the History of Science, Technology, and Medicine, University of Minnesota, 116 Church Street SE, Minneapolis, MN 55455, janss011@umn.edu.

[1] Henry Rowland, "The Highest Aim of the Physicist," *Science*, New Series 10, no. 258 (1899): 825–833, on 828.

[2] Following what seems to be a preference in the physics community, we do not hyphenate compound nouns such as "solid state physics," "condensed matter physics," and "high energy physics."

The sentiments he described would nonetheless color physical investigations of solids and other complex matter throughout the twentieth century. Solid state physics often drew sneers from those who fancied that their own studies attained a greater degree of elegance. At the same time, it posed gnarly conceptual and practical problems that inspired noteworthy leaps of theoretical imagination and experimental virtuosity. The articles presented here explore that duality. Together, they show how sustained attention to solid state physics and associated fields can enrich and perhaps even reform historical understanding of twentieth-century physics.

These papers originated in a session that one of us (JDM) organized for the 2011 meeting of the History of Science Society in Cleveland entitled "Solid State Science in the Twentieth Century: Major Trends through a New Lens." The session responded to the challenge posed in *Out of the Crystal Maze: Chapters from the History of Solid-State Physics*, the first systematic attempt to tell the history of solid state physics. The editors noted that their work was not intended to be comprehensive, but rather that they would assess the book's success "above all by the extent to which our work stimulates others to carry on the study of the subject."[3] Few have responded to their challenge. This introductory essay gives some indication as to why that is, describes how the papers presented here extend the historiographical project *Crystal Maze* launched, and rebroadcasts its rallying cry to a new generation of scholars.

First, though, we must define what we mean by "solid state physics." In a narrow sense, the term refers to the study of solids with regular crystal lattices. In the much broader sense in

[3] Lillian Hoddeson, Ernest Braun, Jürgen Teichmann, and Spencer Weart, eds., *Out of the Crystal Maze: Chapters from the History of Solid-State Physics* (Oxford: Oxford University Press, 1992), xiv.

which we will use it, however, “solid state physics” encompasses much of the subject matter of what is now called “condensed matter physics.”[4] When the American Physical Society’s Division of Solid State Physics was formed in 1947, the term quickly came to encompass an unusually wide range of research topics.[5] In addition to investigations into the structure, behavior, and applications of regular crystalline solids such as semiconductors, work on thin films, amorphous materials, molecules, liquids, gels, plasmas, and aerosols, along with techniques involved in magnetic resonance spectroscopy, low temperature research, superfluidity, and superconductivity are just a few of the areas that were grouped under the heading “solid state physics” at one time or another.

Solid state physics is thus a large, heterogeneous, messy field. That messiness is one reason historians have been hesitant to take it on. As the editors of *Crystal Maze* noted: “the field is huge and varied and lacks the unifying features beloved of historians—neither a single

---

[4] On the relation between these two terms see Joseph D. Martin, “What’s in a Name Change? Solid State Physics, Condensed Matter Physics, and Materials Science,” *Physics in Perspective* 17 (2015): 3–32.

[5] On the establishment of the Division of Solid State Physics, see: Spencer Weart, “The Solid Community,” in Hoddeson, et al., *Crystal Maze* (ref. 3), 617–669 and Joseph D. Martin, *Solid Foundations: Structuring American Solid State Physics, 1939–1993* (PhD dissertation, University of Minnesota, 2013). For a history of the discipline in a wider temporal frame and a broader geographical context see: Michael Eckert and Helmut Schubert, *Crystals, Electrons, Transistors: From Scholar’s Study to Industrial* Research (New York: American Institute of Physics, 1990).

hypothesis or set of basic equations, such as quantum mechanics and relativity theory established for their fields, nor a single spectacular and fundamental discovery, as uranium fission did for nuclear technology or the structure of DNA for molecular biology."[6] This assessment invites counterexamples such as the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity and the transistor, both of which were watershed moments for solid state physics.[7] Transformative as they were, however, neither these developments nor any other proved powerful enough to subjugate the diversity of solid state physics to a common theoretical regime, experimental program, or technical enterprise.

Solid state physics does not lend itself to tidy historical narratives. Asking the standard questions historians of science have been acculturated to take as starting points—What is it that solid state physicists did? What methods did they use? What theoretical programs did they develop? How did their institutions function? How did they influence their social and cultural

---

[6] Hoddeson, et al., *Crystal Maze* (ref. 3), viii.

[7] On the legacy of BCS theory see: Leon N. Cooper and Dmitri Feldman (eds.), *BCS: 50 Years* (Singapore: World Scientific, 2011) and Jean Matricon and Georges Waysand, *The Cold Wars: A History of Superconductivity*, trans. Charles Glashausser (New Brunswick, N.J.: Rutgers University Press, 2003). The discovery and influence of the transistor are chronicled in: Lillian Hoddeson, "The Discovery of the Point-Contact Transistor," *Historical Studies of the Physical Sciences* 12 (1981): 41–76; Michael Riordan, Lillian Hoddeson, and Conyers Herring, "The Invention of the Transistor," *Reviews of Modern Physics* 71, no. 2 (1999): S336–S345; Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Invention of the Transistor and the Birth of the Information Age* (New York: W. W. Norton & Co., 1997).

environment and how did that environment influence them?—leads to a set of answers too diverse to suggest a graceful narrative arc. Historical work on solid state physics has therefore tended towards more readily delineated subjects, such as low temperature physics,[8] semiconductor technology,[9] various instruments and investigative techniques,[10] or the distinctive features of specific institutional or national contexts.[11] These studies have enriched our understanding of both the topical breadth and international reach of solid state physics. They have not, however, gone so far as to challenge the assumption that its history is, in the words of

---

[8] Kostas Gavroglu, ed., *History of Artificial Cold, Scientific, Technological, and Cultural Issues* (Dordrecht: Springer, 2014).

[9] Riordan and Hoddeson, *Crystal Fire* (ref. 7).

[10] Robert P. Crease, "The National Synchrotron Light Source," pts. 1 and 2, *Physics in Perspective* 10 (2008): 438–467; 11 (2009): 15–45; Catherine Westfall, "A Different Laboratory Tale: Fifty Years of Mössbauer Spectroscopy," *Physics in Perspective* 8 (2006): 189–213; Timothy Lenoir and Christophe Lécuyer, "Instrument Makers and Discipline Builders: The Case of Nuclear Magnetic Resonance," *Perspectives on Science* 3 (1995): 276–345.

[11] Atsushi Katsuki, "A Rough Sketch of History of Solid State Physics in Japan," *Historia Scientiarum* 7 (1997): 108–123; D. Lazarus, "Fausto Fumi and the Emergence of Solid-State Physics in Italy," *Il Nuovo Cimento D* 15, no. 2–3 (1993): 139–142; Paul W. Henriksen. "Solid State Physics Research at Purdue," *Osiris* 3 (1987): 237–260; S. T. Keith and Paul K. Hoch, "Formation of a Research School: Theoretical Solid State Physics at Bristol 1930–54," *The British Journal for the History of Science* 19 (1986): 19–44.

James and Joas in the title of their contribution to this issue, "subsequent and subsidiary" to the central narratives of twentieth-century physics.

The often-tacit assumption that solid state physics is of secondary historical importance can be traced to what might be called the fundamentalist fallacy: the history of physics has reproduced the prestige hierarchies that existed within physics itself.[12] Beginning in the 1960s, particle physicists successfully promulgated a picture—described in Martin's contribution to this volume—in which the most fundamental research, and therefore the most prestigious, took place at the smallest physical scales. Solid state physicists, as a result, routinely labored against insinuations that their work amounted to little more than glorified engineering. Wolfgang Pauli, who himself made early contributions to the electron theory of metals, derided the physics of solids as "*Schmutzphysik*" ("physics of dirt"). The analogous English gibe is credited to Murray Gell-Mann, who reportedly dismissed solid state physics as "squalid state physics."[13] These pejorative judgments might be shrugged off as jocose banter among subfields competing for the same funding and institutional authority if they did not reflect a disciplinary power dynamic skewed steeply in favor of nuclear and particle physics. The physicists who had built the bomb,

[12] This argument is developed more fully in Martin, *Solid Foundations* (ref. 5).

[13] These quips have been so often repeated—mostly, as Christian Joas observes, by solid state physicists themselves in their efforts to build solidarity against the derision they indicated—that their origins are obscure. Christian Joas, "Campos que interagem: Física quântica e a transferência de conceitos entre física de partículas, nuclear e do estado sólido," in *Teoria quântica: Estudos históricos e implicações culturais,* ed. Olival Freire Jr., Osvaldo Pessoa Jr., and Joan Lisa Bromberg (Campina Grande, Brasil: Livraria da física, 2011), 109–151.

and who controlled nuclear reactors and particle accelerators, defined what physics was both in the public imagination and in the halls of government, where they remained influential through the end of the century. Solid state physicists, for their part, made notable contributions to World War II research and to Cold War economic and defense priorities. Radar, however, did not play on popular anxieties the way nuclear weapons did and even though microelectronics and improved materials were more present in daily life than accelerators and reactors they did not garner the same level of attention from policymakers.[14] Nuclear and particle physicists also crafted powerful unity narratives that captured both the popular and historical imagination.[15] The ancillary role solid state physics was given in these narratives is reflected in historians' first approaches to the physics of the twentieth century.

The systematic preference for histories told from the perspective of nuclear and particle physics—most especially the latter—is a collective phenomenon. It will be evident from any broad literature survey that the historiography overwhelmingly engages a narrow selection of

---

[14] Spencer Weart considers the psychological power of the atomic nucleus and its consequences in *The Rise of Nuclear Fear* (Cambridge, MA: Harvard University Press, 2012).

[15] See: Peter Galison and David J. Stump, eds., *The Disunity of Science: Boundaries, Contexts, and Power* (Stanford: Stanford University Press, 1996); Jordi Cat, "The Physicists' Debates on Unification in Physics at the End of the 20th Century," *Historical Studies in the Physical Sciences* 28 (1998): 253–299, and Nasser Zakariya, "Making Knowledge Whole: Genres of Synthesis and Grammars of Ignorance," *Historical Studies in the Natural Sciences* 42 (2012): 432–475.

subfields.[16] The most aptly titled example of this trend is *Inward Bound*, Abraham Pais's sweeping history in which the growth of particle accelerators and the refinement of the standard model of particle physics frame a story of twentieth-century physics as an intrepid journey into the atomic nucleus.[17] Rarely is the focus on particle physics as the basis for the rest of the discipline so restrictive and explicit as in *Inward Bound*, yet particle physics has stood in for physics in general in many of the most influential historiographical movements of recent years. Historians of physics think about the relationship between theory and experiment and the nature of physical knowledge through the lens of bubble chambers, weak neutral currents, and quarks.[18] We approach pedagogy through Feynman diagrams.[19] Our understanding of laboratory culture is

---

[16] The EBSCOhost History of Science, Technology, & Medicine database, for example, returns 882 results for a search for "'high energy physics' OR 'particle physics' OR 'nuclear physics'" and 65 for "'molecular physics' OR 'chemical physics' OR 'solid state physics' OR 'condensed matter physics.'" EBSCOhost, "History of Science, Technology & Medicine," web.b.ebscohost.com, accessed 18 Dec 2014.

[17] Abraham Pais, *Inward Bound: Of Matter and Forces in the Physical World* (Oxford: Oxford University Press, 1988).

[18] Andrew Pickering, *Constructing Quarks: A Sociological History of Particle Physics* (Edinburgh: Edinburgh University Press, 1984); Peter Galison, *How Experiments End* (Chicago: The University of Chicago Press, 1987); Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: The University of Chicago Press, 1997).

[19] David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago: The University of Chicago Press, 2005).

steeped in the stories of SLAC, Lawrence Berkeley Laboratory, and Fermilab.[20] Many of the insights gained in such studies undoubtedly apply more broadly, but others may not, and the only way to find out is through careful historical work on other sub-disciplines of twentieth-century physics.

No single piece of scholarship can be faulted for making the natural choice to draw its examples from the most visible and prestigious subfield of physics. In aggregate, though, this emphasis has illuminated the history of twentieth-century physics so as to cast into shadow those specialties that engaged the preponderance of physicists after World War II. The Division of Solid State Physics has been the American Physical Society's largest since the early 1960s. Bare numbers cannot prove importance, of course, and so it is up to historians to demonstrate how focused attention to solid state physics can recast familiar themes in a new light. In different ways, the three papers brought together in this special issue do just that.

The first one, by Jeremiah James and Christian Joas, was written as part of a much larger project on the history of quantum physics centered at the Max Planck Institute for History of

[20] Sharon Traweek, *Beamtimes and Lifetimes: The World of High Energy Physicists* (Cambridge, MA: Harvard University Press, 1988); John L. Heilbron and Robert W. Seidel, *Lawrence and His Laboratory: A History of the Lawrence Berkeley Laboratory,* Volume I (Berkeley: University of California Press, 1989); Lillian Hoddeson, Adrienne Kolb, and Catherine Westfall, *Fermilab: Physics, the Frontier, and Megascience* (Chicago: The University of Chicago Press, 2008).

Science in Berlin.[21] As such, it engages the extensive literature on the emergence of quantum mechanics in the early decades of the twentieth century. The paper shows how one gains an entirely new perspective on these familiar developments when shifting one's vantage point from atomic physics to solid state physics, or, in the specific case that James and Joas focus on, molecular physics. From the traditional point of view of atomic physics, it looks as if the development of quantum theory went through "the eye of a needle," to use the metaphor introduced by the authors. Seen in these terms, the new quantum mechanics grew around a highly localized innovation the consequences of which were then worked out for other areas. The standard account of the codification of the new theory in formalisms such as the Jordan-Dirac transformation theory and Von Neumann's Hilbert space formalism dovetails nicely with this image.[22] James and Joas, however, draw attention to a raft of concepts—among them tunneling, resonance, and exchange—that either originated or were articulated in efforts to deal with phenomena other than atomic spectra.[23] Such concepts are now considered part and parcel of

[21] For more information visit the home page of the project at http://quantum-history.mpiwg-berlin.mpg.de.

[22] Anthony Duncan and Michel Janssen, "(Never) Mind your *p*'s and *q*'s: Von Neumann versus Jordan on the Foundations of Quantum Theory," *The European Physical Journal H* 38 (2013): 175–259. As evidenced by this citation, one of us pleads guilty to having contributed to the perpetuation of the standard account forcefully called into question here by James and Joas.

[23] As a leading American quantum theorist noted in 1928: "The chemist is apt to conceive of the physicist as some one who is so entranced in spectral lines that he closes his eyes to other phenomena." John H. Van Vleck, "The New Quantum Mechanics," *Chemical Reviews* 5, no. 4

quantum mechanics and have drawn attention from scholars before,[24] but have traditionally been seen as “mere” applications of quantum mechanics understood as a more or less complete theory. James and Joas mobilize the histories of these concepts to reveal the role of their development in the very articulation of quantum mechanics. These so-called “applications” of quantum mechanics, they argue, were critical for solidifying the theory’s foundations.

James and Joas can be said to counter the inward-bound bias of the history of twentieth-century physics from within. The challenge posed by the other two papers in this special issue resonates with work in history of technology that has shown how interdisciplinary fields like materials science, spintronics, and nanotechnology remade both the intellectual and institutional landscapes of the physical sciences in the late-twentieth century.[25] The papers by Martin and

---

(1928): 467–507, on 493. See: Charles Midwinter and Michel Janssen, “Kuhn Losses Regained: Van Vleck from Spectra to Susceptibilities,” in *Research and Pedagogy: A History of Early Quantum Physics through its Textbooks*, ed. Massimiliano Badino and Jaume Navarro (Berlin: Edition Open Access, 2013), 137–205. In the session on history of solid state physics at the 2011 HSS meeting Midwinter presented a paper corroborating the picture James and Joas develop: “Disputed Domains: Controversies over Ferromagnetism 1930–1952.”

[24] See, e.g., Cathryn Carson, “The Peculiar Notion of Exchange Forces,” pts. 1 and 2, “Origins in Quantum Mechanics, 1926–1928,” and “From Nuclear Forces to QED, 1929–1950,” *Studies in History and Philosophy of Modern Physics* 27 (1996): 23–45; 99–131.

[25] See: Bernadette Bensaude-Vincent, “The Construction of a Discipline: Materials Science in the United States,” *Historical Studies in the Physical and Biological Sciences* 31 (2001): 223–248; W. Patrick McCray, “From Lab to iPod: A Story of Discovery and Commercialization in

Wilson reevaluate the history of physics in a manner consonant with this trend. They address familiar topics of the institutional structure of physics and its relation with society while framing new questions from the standpoint of comparatively unfamiliar specialties, much as James and Joas do for the conceptual history of twentieth-century physics. How did philosophical commitments originating within solid state physics shape the institutional development of American physics? How does solid state physics force us to reexamine the categories through which we understand the Cold War as a context for science? The importance of asking these questions, alongside parallel questions about how theoretical contributions made within solid state physics contributed to the foundations of quantum mechanics, becomes clear only when we take solid state physics and allied fields as drivers of twentieth-century science rather than as passengers in a vessel steered by supposedly more fundamental enterprises.

Joseph D. Martin's paper addresses the institutional infrastructure that supported American physics and its interaction with funding agencies and Congress. It combines philosophical analysis not with conceptual history, where it has typically been deployed, but with what would traditionally be termed institutional history. Martin traces various notions of "fundamentality" used in different quarters of the physics community from the period

---

the Post–Cold War Era," *Technology & Culture* 50 (2009): 59–81; Cyrus C. M. Mody and Hyungsub Choi, "From Materials Science to Nanotechnology: Interdisciplinary Center Programs at Cornell University, 1960–2000," *Historical Studies in the Natural Sciences* 43 (2013): 121–161; Matthew N. Eisler, "'The Ennobling Unity of Science and Technology': Materials Sciences and Engineering, the Department of Energy, and the Nanotechnology Enigma," *Minerva* 51 (2013): 225–251.

immediately following World War II to the congressional hearings on the Superconducting Super Collider (SSC) in the late 1980s and early 1990s. He analyzes how these notions helped shape the solid state community and its relation to the particle physics community. Through case studies at the scale of individual research installations, professional communities, and national-level funding debates, respectively, he shows how the various notions of fundamentality in play (reduction, fecundity,[26] emergence) matured into bona fide philosophical positions. This process was driven both by the nature of the research in different parts of the community and by growing funding pressures. The philosophical positions ended up being blunted when pressed into service in the battle, fought in a much bigger public arena, over the funding of the SSC. The ideological stances solid state physicists struck in support of their research and funding efforts, as this paper shows, offered powerful and influential alternatives to the reductionist picture that was so central to particle physics and which is often taken to be characteristic of twentieth-century American physics as a whole.

Benjamin Wilson's paper shows that many of the categories we apply to Cold War science slip out of focus when we examine solid state physics and allied fields. It then builds a roadmap to guide us through a blurrier historical landscape. Wilson traces the development of nonlinear optics, a subspecialty combining elements of optics and solid state physics, which emerged in the 1960s. Wilson shows how American physicists created this new field while shuttling between elite universities and the classified committees advising the US military, complicating distinctions between basic and applied, civilian and military research. This paper

[26] This is the term Martin introduces for fundamentality in the sense of relevance to research in neighboring subjects.

contributes to recent reactions against these and similar categories, while also suggesting how we can recast them in forms that help us better understand the relevant history.[27] A long tradition, tracing to Paul Forman's well-known study of quantum electronics, has considered the influence of military patronage on Cold War physics.[28] Wilson reimagines this tradition by returning a measure of agency to the scientists involved. He builds on studies of laser research by Joan Bromberg and Robert Seidel to challenge some basic assumptions about how military patronage relationships functioned.[29] Focusing on the distinctive social spaces such patronage created, Wilson argues that physicists used these spaces to produce knowledge that was at once basic and relevant to military applications. By the late 1960s, research had dashed any hopes that lasers could be used to intercept ballistic missiles. The researchers involved, however, had, in the course of exploring this option, hit upon key features of the blossoming new field of nonlinear optics. The interstitial space between the ivied halls of the academy and the secretive

---

[27] See: Robert Bud, ed., "Applied Science," focus section, *Isis* 103, no. 2 (2012).

[28] Paul Forman, "Behind Quantum Electronics: National Security as Basis for Physical Research in the United States, 1940–1960," *Historical Studies in the Physical and Biological Sciences* 18 (1987): 149–229.

[29] Joan Lisa Bromberg, "Device Physics vis-à-vis Fundamental Physics in Cold War America: The Case of Quantum Optics," *Isis* 97 (2006): 237–259 and *The Laser in America* (Cambridge, MA: MIT Press, 1991); Robert W. Seidel, "From Glow to Flow: A History of Military Laser Research and Development," *Historical Studies in the Physical and Biological Sciences* 18 (1987): 111–147.

boardrooms of military advisory committees allowed them to transition from unblushingly applied military research to questions of basic conceptual importance, and back again.

The cumulative effect of these papers is to make the history of physics a bit dirtier. As a unit, they suggest that twentieth-century physics writ large is approximated better by the messy, sometimes chaotic development of *Schmutzphysik* than by the cleaner, more straightforward development of particle physics. When we make solid state physics a primary analytical category we see the need to take into account more variables to understand the articulation of physics' theoretical structure. We gain awareness of the complex ideological tug-of-war that guided its institutional development. We become sensitized to the delicate nature of categories like basic and applied research. And we get a panoramic view of the brush that still needs to be cut before we can claim a comprehensive historical understanding of twentieth-century physics.

In 1967, Arthur L. Schawlow, pioneer of laser spectroscopy, wrote to his colleague Felix Bloch: "It may be that the theory of solid and liquid states is now so complicated that one has to allow time for a man to reach a broad perspective."[30] Much the same might have been said for the history of solid state physics not too long ago. *Out of the Crystal Maze* was researched and written in an era when many of the processes that made solid state physics historically important were still maturing. We contend that the time for a broad perspective on the history of solid state physics has now arrived. This special issue indicates the wide range of possibilities for further research at the conceptual, the institutional, and the social/cultural levels. We hope that each of

[30] Arthur L. Schawlow to Felix Bloch, 18 Oct 1967, Felix Bloch papers, Stanford University Archives, Palo Alto, CA, Box 8, Folder 15.

these contributions might turn out to be fundamental in Martin's sense of fecundity and help bring about a much-needed renaissance in the study of the history of solid state physics.

[FIRST LEVEL HEADING] ACKNOWLEDGEMENTS

For helpful commentary on this piece we thank each of the contributors to this special issue. The issue as a whole owes a considerable debt to the deft editorial stewardship of Olivier Darrigol, Michael Gordin, Patrick McCray, and Andrea Woody.